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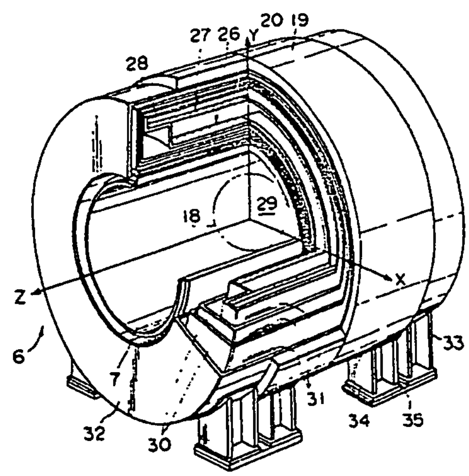
(54) Magnet apparatus for use in magnetic resonance imaging system.

(57) A magnet apparatus (6) for use in a magnetic resonance imaging system includes a first superconducting coil assembly (26), arranged radially outside a bore (7), for generating a first magnetic field in a working volume (18). An active magnetic shield (27) which includes a second superconducting coil assembly for generating a second magnetic field, the direction of which is opposite to that of the first magnetic field, in the working volume (18), is arranged radially outside the bore (7). A yoke magnetic shield (19) formed of a ferromagnetic material is arranged radially outside the first superconducting coil assembly (26) and the active magnetic shield (27). Magnetic fluxes of the first and second magnetic fields leaking outside the bore cancel each other to be attenuated, and are absorbed in the yoke magnetic shield (19). A magnetic fringe field is reduced by a combination of the active and yoke magnetic shields (27, 19), and a magnetic field in the working volume (18) is set at a high homogeneity.



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Magnet apparatus for use in magnetic resonance imaging system

The present invention relates to a magnet apparatus for use in a magnetic resonance imaging system (MRI system) and, more particularly, to a magnet apparatus having a magnetic shield for reducing a magnetic fringe field.

An MRI apparatus is provided with a bore, and a working volume where a portion to be diagnosed of a patient is located is defined in the bore. A magnet apparatus has a main superconducting coil which is arranged to surround the bore and generates a static or main magnetic field in the working volume. A gradient magnetic field is superposed on the static magnetic field, and a high-frequency signal is applied to the portion to be diagnosed of the patient. As a result, a magnetic resonance signal generated by the portion to be diagnosed is detected, thus obtaining a tomographic image of the portion.

Magnetic fluxes of the static magnetic field leak from the bore, and a magnetic fringe field is formed outside the bore. The magnetic fringe field often magnetically adversely influences a portion around the MRI apparatus. For this reason, a magnetic shield for reducing the magnetic fringe field is provided to the magnet apparatus. Conventionally, as the magnetic shield, a yoke magnetic shield and an active magnetic shield are known.

The yoke magnetic shield comprises a cylindrical member surrounding the static magnetic field superconducting coil and formed of a ferromagnetic member. The magnetic fluxes leaking from the bore are absorbed by the magnetic shield, thus reducing the magnetic fringe field. However, when the intensity of the static magnetic field is increased, an amount of leaking magnetic fluxes is also increased. For this reason, an amount of a magnetic material of the cylindrical member must be increased in correspondence with an increase in intensity of the static magnetic field. As a result, the weight of the magnetic shield is considerably increased.

For example, when a 5,000-Gauss main superconducting coil is used, a magnetic shield formed of about 5 tons of iron can provide a 5-Gauss magnetic fringe field region of about 40 m^2. However, when a 15,000-Gauss main superconducting coil is used, a magnetic shield formed of about 40 tons of iron is required so as to provide a 5-Gauss magnetic fringe field region of the same area. It is impossible to install an MRI system comprising such a magnetic shield in an existing hospital.

In addition, even if the static magnetic field intensity is changed during the operation of the MRI system, an absorbing amount of the leaking magnetic fluxes by the yoke magnetic shield cannot be controlled in correspondence with a change in intensity.

On the other hand, the active magnetic shield comprises a second superconducting magnetic coil for generating a second magnetic field in a direction opposite to that of the magnetic field generated by the main superconducting coil in the working volume. Outside the bore, the intensity of the magnetic field generated by the main coil is almost equal to that of the magnetic field generated by the second coil. For this reason, leaking magnetic fluxes of these two magnetic fields cancel each other, thus reducing the magnetic fringe field. On the other hand, in the working volume, the two magnetic fields are synthesized to form a static magnetic field. A difference between the intensities of the two magnetic fields is set to provide a predetermined static magnetic field intensity.

Since the active magnetic shield does not require a ferromagnetic member, its weight is smaller than the yoke magnetic shield. In addition, a current flowing through the second coil can be adjusted so as to control a suppression amount of the leaking magnetic fluxes.

However, since a difference between the intensities of the two magnetic fields is set to be the predetermined static field intensity, the number of turns of superconducting wires of the two superconducting coils must be very large. For this purpose, a large amount of superconducting wires are required. As a result, the magnet apparatus has high manufacturing cost.

Furthermore, the second coil is arranged radially outside the main coil. For this reason, the outer diameter of the magnet apparatus is considerably increased. As a result, when the magnet apparatus is transported or when the magnet apparatus is installed, a very large transportation space and installation space are necessary. An existing hospital often does not have such a large transportation space and installation space, and a passage and installation space in the hospital must sometimes be reconstructed or additionally constructed. Therefore, it is difficult to transport and install the magnet apparatus.

In a building such as a hospital, magnetic members such as reinforcements arranged in columns and floors are provided. The magnetic flux densities of the magnetic fluxes of the two magnetic fields may be changed by these magnetic members outside the bore. The magnetic fluxes whose density is changed may enter the working volume of the bore. As a result, homogeneity of the magnetic field in the working volume is deteriorated, and MRI diagnosis is disturbed.

It is an object of the present invention to provide a magnet apparatus for use in a magnetic resonance imaging system, can be small in size and in weight so that the magnet apparatus which can be easily carried and installed in an existing hospital or the like, can reduce its manufacturing cost, and is free from the magnetic influence from magnetic members of an installation facility.

It is another object of the present invention to provide a magnet apparatus for use in a magnetic resonance imaging system, which can maintain a magnetic field at a high homogeneity in a working volume in a bore, and can reduce a magnetic fringe field.

According to the present invention, there is provided a magnet apparatus for use in a magnetic resonance imaging system, the system having a bore housing an object to be examined, and a working volume where a portion to be diagnosed of the object to be examined is located being defined in the bore, the magnetic apparatus comprising a first superconducting coil assembly, arranged radially outside the bore, for generating a first magnetic field in the working volume, an active magnetic shield including a second superconducting coil assembly, arranged radially outside the bore and electrically connected in series with the first superconducting coil assembly, for generating a second magnetic field in a direction opposite to the direction of the first magnetic field in the working volume, and a yoke magnetic shield, arranged radially outside the first superconducting coil assembly and the active magnetic shield and formed of a ferromagnetic member, whereby most of magnetic fluxes of the first and second magnetic fields leaking outside the bore cancel each other to be weakened and are absorbed in the yoke magnetic shield so as to reduce an amount of leaking magnetic fluxes, some of the magnetic fluxes of the first and second magnetic fields leaking outside the bore are magnetically changed by the yoke magnetic shield and enter the bore to form a third magnetic field in the working volume, and the first to third magnetic fields are synthesized in the working volume to form a synthesized magnetic field.

Furthermore, in an embodiment of the present invention, means for setting a synthesized magnetic field in the working volume at a high homogeneity is arranged.

Therefore, a magnetic fringe field can be reduced by cooperation of an active magnetic shield and a yoke magnetic shield, and the synthesized magnetic field in the working volume is maintained at a high homogeneity. For this reason, the volumes of the active and yoke magnetic shields can be reduced to be smaller than those of the conventional shields.

As a result, the magnet apparatus can be rendered compact and light in weight. Thus, the magnet apparatus can be easily carried and installed in an existing hospital or the like.

Furthermore, an amount of use of a superconducting wire can be reduced, and the manufacturing cost of the magnet apparatus can be reduced.

In this invention, a magnetic fringe field is absorbed by the yoke magnetic shield. For this reason, a magnetic fringe field reaching ferromagnetic members such as reinforcements arranged in columns and floors can be eliminated. Thus, a magnetic fringe field whose magnetic flux density is changed by these ferromagnetic members enters the working volume less often. Therefore, homogeneity of the magnetic field in the working volume can be prevented from being deteriorated by the influence of the ferromagnetic members such as reinforcements arranged in columns and floors.

This invention can be more fully understood from the following detailed description when taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a perspective view and a block diagram of an MRI system;

Fig. 2 is a partially cutaway perspective view of a magnet apparatus according to the present invention;

Fig. 3 is a horizontal sectional view of the magnet apparatus shown in Fig. 2;

Fig. 4 is a horizontal sectional view of a magnet apparatus according to a first modification of the present invention; and

Fig. 5 is a horizontal sectional view of a magnet apparatus according to a second modification of the present invention.

Fig. 1 shows a magnetic resonance imaging system (MRI system) in which a magnet apparatus as an object of the present invention is applied is used.

A patient 1 lying on a couch 2 is housed in a warm bore 7. A portion to be diagnosed of the patient 1 is located in a working volume 18. A magnet apparatus 6 generates a static or main magnetic field in the working volume 18 along a Z axis. The magnet apparatus 6 is connected to an excitation power source 8. X, Y, and Z gradient magnetic field coils 5 are arranged radially inside the magnet apparatus 6. These coils 5 are connected to excitation power sources 11, 12, and 13, respectively.

Furthermore, an RF coil 3 is arranged to surround the portion to be diagnosed of the patient 1. The RF coil 3 is connected to an RF transmitter 15 and an RF receiver 16. The RF transmitter 15, the RF receiver

16, and the excitation power sources 11, 12, and 13 are connected to a central control unit 14. The control unit 14 is connected to a display/operation console 17.

The magnet apparatus 6 is excited, and as a result, generates a uniform static magnetic field in the working volume. In this case, X, Y, and Z gradient magnetic fields generated by the X, Y, and Z gradient magnetic field coils 5 are superposed on the static magnetic field. At the same time, the RF transmitter 15 is driven by a pulse sequence to apply a pulse signal. Thus, a magnetic resonance signal is induced in the portion to be diagnosed of the patient. The magnetic resonance signal is detected by the RF coil 3, and is fetched in the central control unit 14 through the RF receiver 16. The central control unit 14 performs image reproduction processing to obtain image data. The image data is converted to a video signal, and a tomographic image is displayed on the display/operation console 17.

The magnet apparatus 6 as the object of the present invention will be described below with reference to Figs. 2 and 3.

The magnet apparatus 6 of the present invention comprises a first superconducting coil assembly 26 for generating a first magnetic field constituting most part of the static magnetic field, a cooling means for cooling the superconducting coil, and a means for reducing a magnetic field leaking outside the magnet apparatus 6.

The first superconducting coil assembly 26 surrounds the warm bore 7, and extends along the Z axis. A mid-plane 29 (X-Y plane) of the magnet apparatus 6 is defined to be perpendicular to the Z axis. The first superconducting coil assembly 26 includes a plurality of coaxial coils symmetrically arranged with reference to the mid-plane 29.

The cooling means is constituted by a liquid helium tank 28 filled with a liquid helium and housing the superconducting coil assembly 26, a plurality of heat radiation shield plates 30 covering the liquid helium tank 28, multilayered heat insulating members 31 housed between the adjacent heat radiation shield plates 30, and a vacuum container 32 which covers the heat radiation shield plates 30 and the interior of which is kept in a vacuum state. The vacuum chamber 32 is supported on legs 33. The cooling means keeps the first superconducting coil assembly 26 at a cryogenic state of 4.2 K.

The characteristic feature of the present invention is that the means for eliminating the magnetic fringe field comprises an active magnetic shield 27 and a yoke (passive) magnetic shield 19.

The active magnetic shield 27 comprises a second superconducting coil assembly which is coaxially arranged radially outside the first coil assembly 26. The second superconducting coil assembly includes a plurality of coaxial coils which are symmetrically arranged with reference to the mid-plane 29. Furthermore, the second superconducting coil assembly is housed in the liquid helium tank 28 and is cooled to 4.2 K. The second superconducting coil assembly is connected in series with the first superconducting coil assembly 26, and generates a second magnetic field in a direction opposite to that of the first magnetic field in the working volume 18.

The yoke magnetic shield 19 comprises a cylindrical shell member 20 formed of a ferromagnetic material such as iron and attached on the outer periphery of the vacuum chamber 32, and legs 34 supporting the shell member 20 and coupled to the legs 33 through coupling plates 35. The shell member 20 is arranged concentrically with the first and second superconducting coil assemblies about the Z axis. Furthermore, the shell member 20 is divided into two segments with reference to the mid-plane 29 (X-Y plane). Each of these segments is further divided into two pieces with reference a vertical plane (Y-Z plane) along the Z axis. More specifically, the shell member 20 is divided into four pieces. The length of the shell member 20 along the Z axis is shorter than that of the second superconducting coil assembly.

As shown in Fig. 3, the direction of the first magnetic field is opposite to that of the second magnetic field. For this reason, the magnetic fluxes of the first magnetic field leaking from the bore 7 and those of the second magnetic field leaking therefrom cancel each other to be weakened. The weakened magnetic fluxes are absorbed in the yoke magnetic shield 19. Thus, the leaking magnetic field is reduced.

The yoke magnetic shield electromagnetically forms a third magnetic field in the working volume 18. More specifically, some of the leaking magnetic fluxes of the first and second magnetic fields are magnetically changed by the yoke magnetic shield and enter the working volume 18 to form the third magnetic field. For this reason, the first to third magnetic fields are present in the working volume 18, and form a synthesized magnetic field.

In the MRI system, the magnetic field in the working volume 18 is required to have a high homogeneity, e.g., homogeneity of 20 ppm or less. Therefore, the synthesized magnetic field of the first to third magnetic fields in the working volume 18 is required to have a high homogeneity. For this purpose, according to the present invention, the following means for setting the synthesized magnetic field at a high homogeneity is arranged.

The intensity of the first magnetic field generated by the first superconducting coil assembly is

expressed by a component of a term of degree 0 (degree-0 term component) and components of terms of higher degrees (higher-degree term components, i.e., error components), and is series-developed as follows:

$$
\begin{aligned}
B_M &= B_{0M} + \sum_{i=1}^{\infty} b_{iM} \\
&= B_{0M} + b_{1M} + b_{2M} + \ldots + b_{iM} + \ldots
\end{aligned}
\qquad \ldots(1)
$$

B_M: first magnetic field intensity
B_{0M}: degree-0 term component

$$\sum_{i=1}^{\infty} b_{iM}:$$
$$b_{iM}:$$

higher-degree term components
b_{iM}: term of degree i of the higher-degree term components

The intensity of the second magnetic field generated by the active magnetic shield is expressed by a degree-0 term component and higher-degree term components, and is series-developed as follows:

$$
\begin{aligned}
B_A &= B_{0A} + \sum_{i=1}^{\infty} b_{iA} \\
&= B_{0A} + b_{1A} + b_{2A} + \ldots + b_{iA} + \ldots
\end{aligned}
\qquad \ldots(2)
$$

B_A: first magnetic field intensity
B_{0A}: degree-0 term component

$$\sum_{i=1}^{\infty} b_{iA}:$$
$$b_{iA}:$$

higher-degree term components
b_{iA}: term of degree i of the higher-degree term components

The intensity of the third magnetic field generated by the yoke magnetic shield is expressed by a degree-0 term component and higher-degree term components, and is series-developed as follows:

$$
\begin{aligned}
B_Y &= B_{0Y} + \sum_{i=1}^{\infty} b_{iY} \\
&= B_{0Y} + b_{1Y} + b_{2Y} + \ldots + b_{iY} + \ldots
\end{aligned}
\qquad \ldots(3)
$$

B_Y: first magnetic field intensity
B_{0Y}: degree-0 term component

$$\sum_{i=1}^{\infty} b_{iY}:$$
$$b_{iY}:$$

higher-degree term components

b_{iY}: term of degree i of the higher-degree term components

Therefore, the intensity of the synthesized magnetic field is expressed by degree-0 term components and higher-degree term components as follows:

$$B_M - B_A + B_Y = B_{0M} - B_{0A} + B_{0Y} + \sum_{i=1}^{\infty}(b_{iM} - b_{iA} + b_{iY}) \quad \ldots(4)$$

If the higher-degree term components (i.e., error components)

$$\sum_{i=1}^{\infty}(b_{iM} - b_{iA} + b_{iY})$$

are set to be substantially zero, the intensity of the synthesized magnetic field consists of only the degree-0 term components. Thus, the synthesized magnetic field is set at a high homogeneity.

For this purpose, according to the present invention, the numbers of turns of the superconducting wires of the first and second superconducting coil assemblies and the amount of the ferromagnetic member of the yoke magnetic shield are determined so that the sums of the terms of the same degrees of the higher-degree term components of the first to third magnetic fields are set to be substantially zero, that is, $b_{1M} - b_{1A} + b_{1Y}$ 0, $b_{2M} - b_{2A} + b_{2Y}$ $0, \ldots, b_{iM} - b_{iA} + b_{iY}$ 0. As a result, the intensity of the synthesized magnetic field is defined by only the degree-0 term components $B_{0M} - B_{0A} + B_{0Y}$, and the synthesized magnetic field is set at a high homogeneity.

The means for setting the higher-degree term components of the synthesized magnetic fields to be substantially zero may be arranged as follows.

The number of turns of the superconducting wire of the first superconducting coil assembly is set, so that the terms of the higher-degree term components of the first magnetic field are set to be substantially zero, that is, b_{1M} 0, b_{2M} $0, \ldots, b_{iM}$ 0. Furthermore, the number of turns of the superconducting wire of the second superconducting coil assembly and the amount of the magnetic member of the yoke magnetic shield are set so that the sums of the terms of the same degrees of the higher-degree term components of the second and third magnetic fields are set to be substantially zero, that is, $-b_{1A} + b_{1Y}$ 0, $-b_{2A} + b_{2Y}$ $0, \ldots, -b_{iA} + b_{iY}$ 0. In this case, the intensity of the synthesized magnetic field is defined by only the degree-0 term components, and the synthesized magnetic field is set at a high homogeneity.

Furthermore, the means for setting the higher-degree term components of the synthesized magnetic fields to be substantially zero may be arranged as follows.

The number of turns of the superconducting wire of the second superconducting coil assembly is set, so that the terms of the higher-degree term components of the second magnetic field are set to be substantially zero, that is, b_{1A} 0, b_{2A} $0, \ldots, b_{iA}$ 0. Furthermore, the number of turns of the superconducting wire of the first superconducting coil assembly and the amount of the magnetic member of the yoke magnetic shield are set so that the sums of the terms of the same degrees of the higher-degree term components of the first and third magnetic fields are set to be substantially zero, that is, $b_{1M} + b_{1Y}$ 0, $-b_{2M} + b_{2Y}$ $0, \ldots, b_{iM} + b_{iY}$ 0. In this case, the intensity of the synthesized magnetic field is defined by only the degree-0 term components, and the synthesized magnetic field is set at a high homogeneity.

According to the present invention, as described above, the magnetic fringe field is reduced by a cooperation of the active and yoke magnetic shields, and the synthesized magnetic field in the working volume 18 is set at a high homogeneity. For this reason, the volumes of the active and yoke magnetic shields can be reduced to be smaller than those of the conventional ones.

Since the volume of the active magnetic shield can be reduced, the outer dimensions of the magnet apparatus can be reduced. For this reason, the MRI system can be rendered compact, and can be easily carried and installed in a hospital or the like. Since the volume of the active magnetic shield can be reduced, the amount of use of a superconducting wire can be reduced. Thus, an increase in manufacturing cost of the magnet apparatus can be suppressed.

Since the volume of the yoke magnetic shield can be reduced, the weight of the yoke magnetic shield can be decreased. As a result, the MRI system can be easily carried and installed in a hospital or the like. In addition, the floor structure in the hospital need not be specially reinforced for installation of the MRI system in the hospital.

The magnetic fringe field is absorbed by the yoke magnetic shield. For this reason, leaking magnetic fluxes reaching ferromagnetic members such as reinforcements arranged in columns and floors can be eliminated. For this reason, a leaking magnetic field whose magnetic flux density is changed by these magnetic members enters the working volume less often. Therefore, the homogeneity of the magnetic field in the working volume can be prevented from being deteriorated by the influence of the ferromagnetic members such as reinforcements arranged in columns and floors.

Furthermore, the length, along the Z axis, of the shell member 20 of the yoke magnetic shield is smaller than that of the second superconducting coil. For this reason, disturbance of magnetic fluxes at the end portions of the magnet apparatus 6 in the Z direction can be eliminated. For this reason, the homogeneity of the magnetic field in the working volume 18 can be improved.

The yoke magnetic shield 19 is divided into four pieces and these pieces are carried in a hospital or the like. The pieces are assembled in the hospital. Thus, carry-in and installation of the MRI system in the hospital can be further facilitated. Note that after assembly, the legs 33 of the magnet apparatus and the legs 34 of the yoke magnetic shield 19 are coupled through the coupling plates 35.

A first modification of the present invention will be described below with reference to Fig. 4. In the first modification, a plurality of iron shims 36 are attached to the inner peripheral surface of the warm bore 7. The iron shims 36 serve to finely adjust the shape of lines of magnetic forces in the bore 7, thus improving homogeneity of the magnetic field in the working volume 18.

The iron shims 36 electromagnetically form a fourth magnetic field in the working volume 18. More specifically, some of the magnetic fluxes of the first to third magnetic fields are magnetically changed by the iron shims 36, thus forming the fourth magnetic field in the working volume 18. For this reason, the first to fourth magnetic fields are present in the working volume 18, and form a synthesized magnetic field.

In this case, a means for setting the synthesized magnetic field at a high uniformity level is arranged as follows.

The intensity of the fourth magnetic field is expressed by a degree-0 term component and higher-degree term components (i.e., error components), and is series-developed as follows:

$$\begin{aligned} B_S &= B_{0S} + \sum_{i=1}^{\infty} b_{iS} \\ &= B_{0S} + b_{1S} + b_{2S} + \dots + b_{iS} + \dots \end{aligned} \qquad \dots(5)$$

B_S: first magnetic field intensity
B_{0S}: degree-0 term component

$$\sum_{i=1}^{\infty} b_{iS}:$$
$$b_{iS}:$$

higher-degree term components
b_{iS}: term of degree i of the higher-degree term components

Therefore, from equations (1) to (3) and equation (5), the intensity of the synthesized magnetic field is expressed as follows

$$\begin{aligned} B_M - B_A + B_Y + B_S = {} & B_{0M} - B_{0A} + B_{0Y} + B_{0S} \\ & + \sum_{i=1}^{\infty} (b_{iM} - b_{iA} + b_{iY} + b_{iS}) \end{aligned} \qquad \dots(6)$$

If the higher-degree term components (i.e., error components)

$$\sum_{i=1}^{\infty}(b_{iM} - b_{iA} + b_{iY} + b_{iS})$$

are set to be substantially zero, the intensity of the synthesized magnetic field consists of only the degree-0 term components. Thus, the synthesized magnetic field is set at a high homogeneity.

For this purpose, in the first modification, the numbers of turns of the superconducting wires of the first and second superconducting coil assemblies and the amounts of the magnetic members of the yoke magnetic shield and the iron shims are determined so that the sums of the terms of the same degrees of the higher-degree term components of the first to fourth magnetic fields is set to be substantially zero, that is, $b_{1M} - b_{1A} + b_{1Y} + b_{1S}$ 0,..., $b_{iM} - b_{iA} + b_{iY} + b_{iS}$ 0. As a result, the intensity of the synthesized magnetic field is defined by only the degree-0 term components $B_{0M} - B_{0A} + B_{0Y} + B_{0S}$, and the synthesized magnetic field is set at a high homogeneity.

The means for setting the higher-degree term components of the synthesized magnetic fields to be substantially zero may be arranged as follows.

The number of turns of the superconducting wire of the first superconducting coil assembly is set, so that the terms of the higher-degree term components of the first magnetic field are set to be substantially zero, that is, b_{1M} 0,..., b_{iM} 0. Furthermore, the number of turns of the superconducting wire of the second superconducting coil assembly and the amounts of the magnetic members of the yoke magnetic shield and the iron shims are set so that the sums of the terms of the same degrees of the higher-degree term components of the second and fourth magnetic fields are set to be substantially zero, that is, $-b_{1A} + b_{1Y} + b_{1S}$ 0,..., $-b_{iA} + b_{iY} + b_{iS}$ 0. In this case, the intensity of the synthesized magnetic field is defined by only the degree-0 term components, and the synthesized magnetic field is set at a high homogeneity.

Furthermore, the means for setting the higher-degree term components of the synthesized magnetic fields to be substantially zero may be arranged as follows.

The number of turns of the superconducting wire of the second superconducting coil assembly is set, so that the terms of the higher-degree term components of the second magnetic field are set to be substantially zero, that is, $-b_{1A}$ 0,..., $-b_{iA}$ 0. Furthermore, the number of turns of the superconducting wire of the first superconducting coil assembly and the amounts of the magnetic members of the yoke magnetic shield and the iron shims are set so that the sums of the terms of the same degrees of the higher-degree term components of the first, third, and fourth magnetic fields are set to be substantially zero, that is, $b_{1M} + b_{1Y} + b_{1S}$ 0,..., $b_{iM} + b_{iY} + b_{iS}$ 0. In this case, the intensity of the synthesized magnetic field is defined by only the degree-0 term components, and the synthesized magnetic field is set at a high homogeneity.

Therefore, in the first modification, the synthesized magnetic field in the working volume can be set at a high homogeneity, and a magnetic fringe field can be reduced.

A second modification of the present invention will now be described with reference to Fig. 5.

In the second modification, the yoke magnetic shield 19 has disk-shaped lid members 21 attached to two ends of the shell member 20. The lid members 21 can absorb magnetic fluxes leaking from the bore 7 along the z axis. As a result, the magnetic fringe field along the Z axis can be further reduced.

Claims

1. A magnet apparatus for use in a magnetic resonance imaging system, said system having a bore (7) housing an object to be examined, and a working volume (18) where a portion to be diagnosed of the object to be examined is located being defined in the bore, said magnetic apparatus (6) characterized by comprising:
a first superconducting coil assembly (26), arranged radially outside the bore (7), for generating a first magnetic field in the working volume (18);
an active magnetic shield (27) including a second superconducting coil assembly, arranged radially outside the bore (7) and electrically connected in series with said first superconducting coil assembly (26), for generating a second magnetic field in a direction opposite to the direction of the first magnetic field in the working volume (18); and
a yoke magnetic shield (19), arranged radially outside said first superconducting coil assembly (26) and

said active magnetic shield (27) and formed of a ferromagnetic member,
whereby most of magnetic fluxes of the first and second magnetic fields leaking outside the bore cancel each other to be weakened and are absorbed in said yoke magnetic shield (19) so as to reduce an amount of leaking magnetic fluxes,
some of the magnetic fluxes of the first and second magnetic fields leaking outside the bore are magnetically changed by said yoke magnetic shield (19) and enter the bore to form a third magnetic field in the working volume (18), and
the first to third magnetic fields are synthesized in the working volume (18) to form a synthesized magnetic field.

2. An apparatus according to claim 1, characterized in that
an intensity (B_M) of the first magnetic field is expressed by a sum of a degree-0 term component (B_{0M}) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} b_{iM}\right)$$

where i is a natural number,
an intensity (B_A) of the second magnetic field is expressed by a sum of a degree-0 term component (B_{0A}) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} b_{iA}\right),$$

an intensity (B_Y) of the third magnetic field is expressed by a sum of a degree-0 term component (B_{0Y}) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} b_{iY}\right),$$

an intensity ($B_M - B_A + B_Y$) of the synthesized magnetic field is expressed by a sum of degree-0 term components ($B_{0M} - B_{0A} + B_{0Y}$) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} (b_{iM} - b_{iA} + b_{iY})\right),$$

the higher-degree term components of the synthesized magnetic field are set to be substantially zero, that is,

$$\sum_{i=1}^{\infty} (b_{iM} - b_{iA} + b_{iY}) \approx 0$$

whereby the intensity of the synthesized magnetic field consists of only the degree-0 term components and the synthesized magnetic field is set at a high homogeneity.

3. An apparatus according to claim 2, characterized in that
sums of terms of the same degrees of the higher-degree term components of the first to third magnetic fields are set to be substantially zero, that is,
$b_{iM} - b_{iA} + b_{iY} \approx 0$
whereby the higher-degree term components of the synthesized magnetic field are set to be substantially zero.

4. An apparatus according to claim 2, characterized in that
the terms of the higher-degree components of the first magnetic field are set to be substantially zero, that is, $b_{iM} \approx 0$, and sums of terms of the same degrees of the higher-degree term components of the second

and third magnetic fields are set to be substantially zero, that is, $-b_{iA} + b_{iY} \approx 0$, whereby the higher-degree term components of the synthesized magnetic field are set to be substantially zero.

5. An apparatus according to claim 2, characterized in that the terms of the higher-degree components of the second magnetic field are set to be substantially zero, that is, $b_{iA} \approx 0$, and sums of terms of the same degrees of the higher-degree term components of the first and third magnetic fields are set to be substantially zero, that is, $b_{iM} + b_{iY} \approx 0$, whereby the higher-degree term components of the synthesized magnetic field is set to be substantially zero.

6. An apparatus according to claim 1, characterized by further comprising: ferromagnetic shims (36) arranged to surround the bore, wherein some of the magnetic fluxes of the first to third magnetic fields leaking outside the bore are magnetically changed by said ferromagnetic shims (36) and enter the bore to form a fourth magnetic field in the working volume (18), and the first to fourth magnetic fields are synthesized in the working volume (18) to form a synthesized magnetic field.

7. An apparatus according to claim 6, characterized in that an intensity (B_M) of the first magnetic field is expressed by a sum of a degree-0 term component (B_{0M}) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} b_{iM}\right)$$

where i is a natural number, an intensity (B_A) of the second magnetic field is expressed by a sum of a degree-0 term component (B_{0A}) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} b_{iA}\right),$$

an intensity (B_Y) of the third magnetic field is expressed by a sum of a degree-0 term component (B_{0Y}) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} b_{iY}\right),$$

an intensity (B_S) of the fourth magnetic field is expressed by a sum of a degree-0 term component (B_{0S}) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} b_{iS}\right),$$

an intensity ($B_M - B_A + B_Y + B_S$) of the synthesized magnetic field is expressed by a sum of degree-0 term components ($B_{0M} - B_{0A} + B_{0Y} + B_{0S}$) and higher-degree term components

$$\left(\sum_{i=1}^{\infty} (b_{iM} - b_{iA} + b_{iY} + b_{iS})\right),$$

the higher-degree term components of the synthesized magnetic field are set to be substantially zero, that is,

$$\sum_{i=1}^{\infty} (b_{iM} - b_{iA} + b_{iY} + b_{iS}) \approx 0$$

whereby the intensity of the synthesized magnetic field consists of only the degree-0 term components and the synthesized magnetic field is set at a high uniformity level.

8. An apparatus according to claim 7, characterized in that
the sums of terms of the same degrees of the higher-degree term components of the first to fourth magnetic fields are set to be substantially zero, that is,
$b_{lM} - b_{lA} + b_{lY} + b_{lS} \approx 0$
whereby the higher-degree term components of the synthesized magnetic field are set to be substantially zero.

9. An apparatus according to claim 7, characterized in that
the terms of the higher-degree components of the first magnetic field are set to be substantially zero, that is, $b_{lM} \approx 0$, and sums of terms of the same degrees of the higher-degree term components of the second to fourth magnetic fields are set to be substantially zero, that is, $-b_{lA} + b_{lY} + b_{lS} \approx 0$,
whereby the higher-degree term components of the synthesized magnetic field are set to be substantially zero.

10. An apparatus according to claim 7, characterized in that
the terms of the higher-degree components of the second magnetic field are set to be substantially zero, that is, $b_{lA} \approx 0$, and sums of terms of the same degrees of the higher-degree term components of the first, third, and fourth magnetic fields are set to be substantially zero, that is, $b_{lM} + b_{lY} + b_{lS} \approx 0$,
whereby the higher-degree term components of the synthesized magnetic field are set to be substantially zero.

11. An apparatus according to claim 1, characterized in that
said magnet apparatus (6) has a magnetic central axis (Z axis) of said first superconducting coil assembly (26), which extends in the working volume (18) in a direction of the first magnetic field, and a mid-plane (29) of said magnet apparatus (6), which is perpendicular to the magnetic central axis, and
said first superconducting coil assembly (26) includes a plurality of coaxial coils arranged symmetrically with reference to the mid-plane (29).

12. An apparatus according to claim 1, characterized in that
said magnet apparatus (6) has a magnetic central axis (Z axis) of said first superconducting coil assembly (26), which extends in the working volume (18) in a direction of the first magnetic field, and a mid-plane (29) of said magnet apparatus (6), which is perpendicular to the magnetic central axis, and
said second superconducting coil assembly (27) includes a plurality of coaxial coils arranged symmetrically with reference to the mid-plane.

13. An apparatus according to claim 1,
characterized in that
said magnet apparatus (6) has a magnetic central axis (Z axis) of said first superconducting coil assembly (26), which extends in the working volume (18) in a direction of the first magnetic field, and a mid-plane (29) of said magnet apparatus (6), which is perpendicular to the magnetic central axis, and
said yoke magnetic shield (19) is arranged symmetrically with reference to the mid-plane (29).

14. An apparatus according to claim 13, characterized in that said yoke magnetic shield (19) includes a cylindrical shell member (20) formed of a ferromagnetic material.

15. An apparatus according to claim 14, characterized by further comprising: a vacuum container (32) for maintaining said first and second superconducting coil assemblies (26, 27) in a cryogenic state,
wherein a length of said cylindrical shell member (20) along the magnetic central axis is smaller than that of said vacuum container (32).

16. An apparatus according to claim 15, characterized in that
a length of said cylindrical shell member (20) along the magnetic central axis is larger than that of said first superconducting coil assembly (26) and is smaller than that of said second superconducting coil assembly (27).

17. An apparatus according to claim 15, characterized in that
a length of said cylindrical shell member (20) along the magnetic central axis is smaller than that of said first superconducting coil assembly (26).

18. An apparatus according to claim 14, characterized in that
said yoke magnetic shield (19) includes members (21), attached to two end portions of said shell member (20) and formed of a ferromagnetic material, for absorbing magnetic fluxes of the first and second magnetic fields leaking outside the bore.

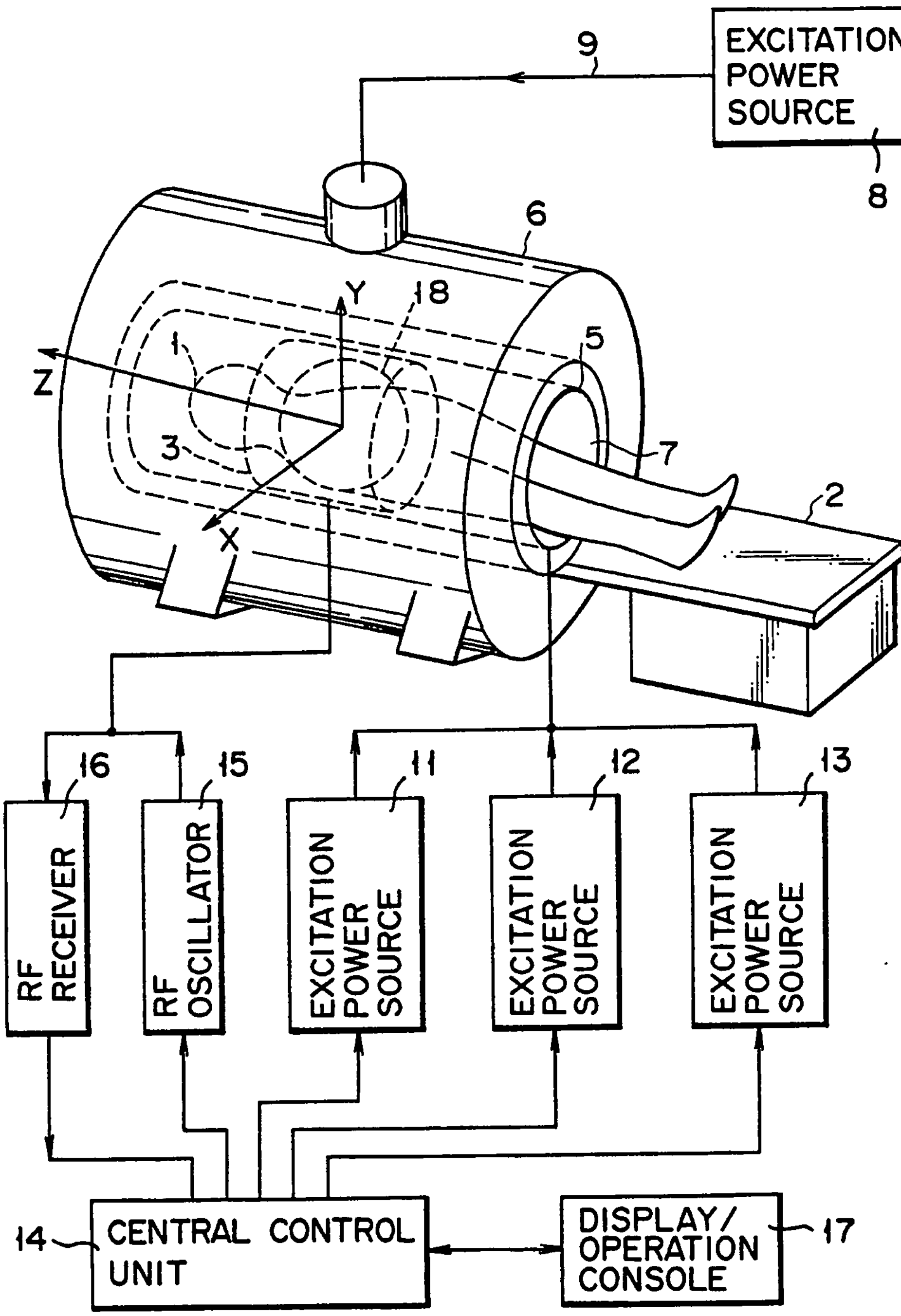
19. An apparatus according to claim 14, characterized in that
said cylindrical shell member (20) is divided into a plurality of segments.

20. An apparatus according to claim 19, characterized in that
said cylindrical shell member (20) is divided into two segments by the mid-plane (29).

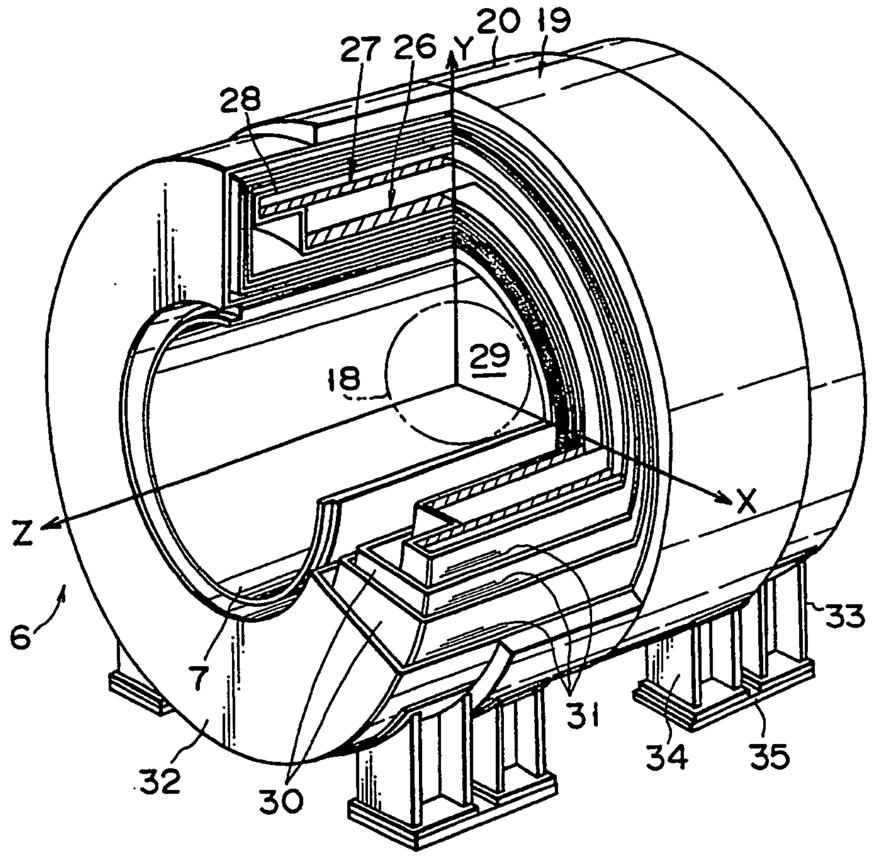
21. An apparatus according to claim 19, characterized in that
said cylindrical shell member (20) is divided into two segments by a flat plane along the magnetic central axis.

22. An apparatus according to claim 19, characterized in that
said cylindrical shell member (20) is divided into four segments by flat planes respectively along the mid-plane (29) and the magnetic central axis.

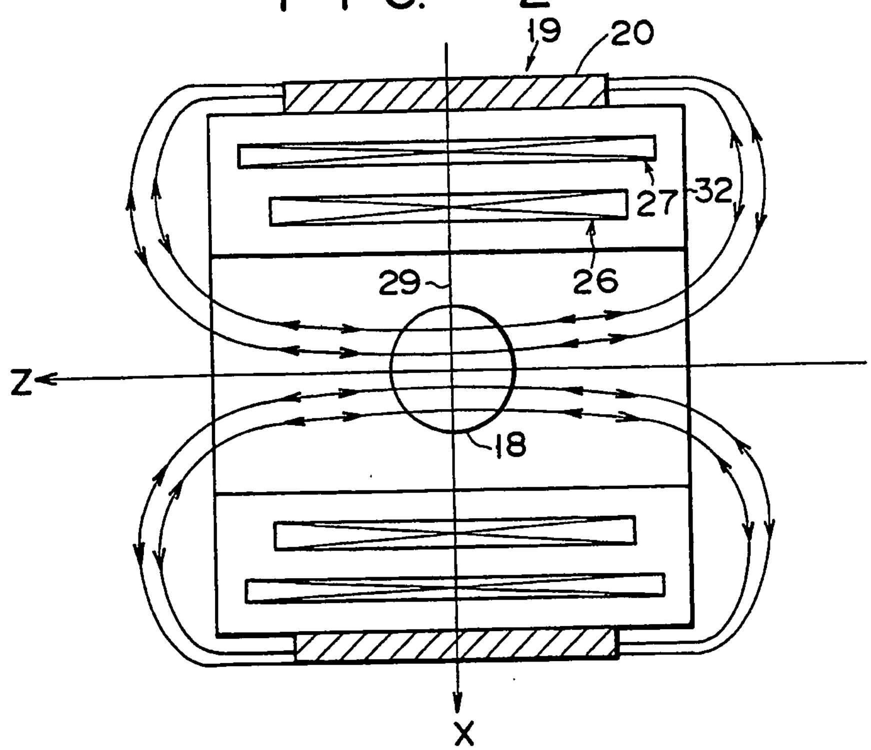
23. An apparatus according to claim 1, characterized in that
said magnet apparatus (6) has a magnetic central axis (Z axis) of said first superconducting coil assembly (26), which extends in the working volume (18) in a direction of the first magnetic field, and
said first and second superconducting coil assemblies (26, 27) and said yoke magnetic shield (19) are coaxially arranged about the magnetic central axis.


EXCITATION POWER SOURCE
9
8
6
Y
18
Z
1
5
3
7
2
X
16
15
11
12
13
RF RECEIVER
RF OSCILLATOR
EXCITATION POWER SOURCE
EXCITATION POWER SOURCE
EXCITATION POWER SOURCE
14
CENTRAL CONTROL UNIT
DISPLAY/ OPERATION CONSOLE
17

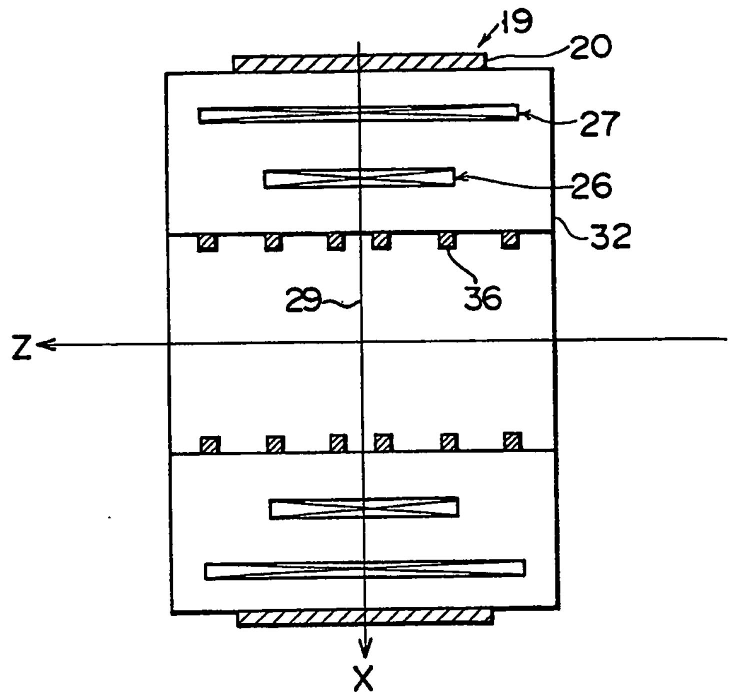
F I G. 1



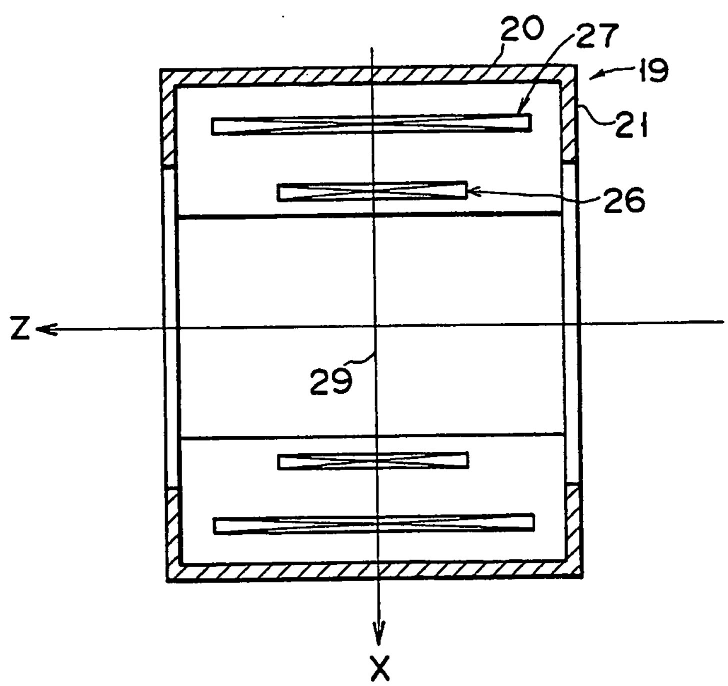
F I G. 2



F I G. 3



F I G. 4



F I G. 5

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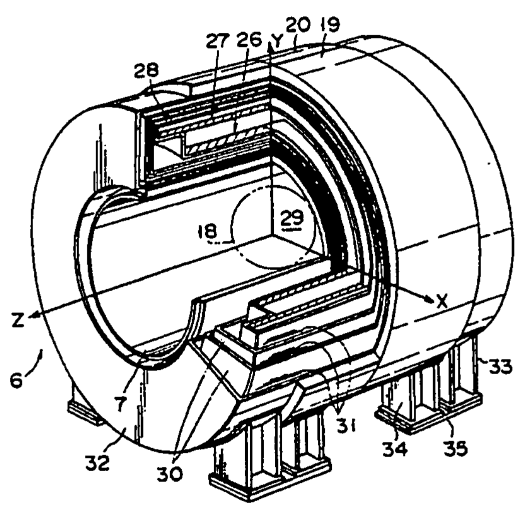
(54) **Magnet apparatus for use in magnetic resonance imaging system.**

(57) A magnet apparatus (6) for use in a magnetic resonance imaging system includes a first superconducting coil assembly (26), arranged radially outside a bore (7), for generating a first magnetic field in a working volume (18). An active magnetic shield (27) which includes a second superconducting coil assembly for generating a second magnetic field, the direction of which is opposite to that of the first magnetic field, in the working volume (18), is arranged radially outside the bore (7). A yoke magnetic shield (19) formed of a ferromagnetic material is arranged radially outside the first superconducting coil assembly (26) and the active magnetic shield (27). Magnetic fluxes of the first and second magnetic fields leaking outside the bore cancel each other to be attenuated, and are absorbed in the yoke magnetic shield (19). A magnetic fringe field is reduced by a combination of the active and yoke magnetic shields (27, 19), and a magnetic field in the working volume (18) is set at a high homogeneity.



F I G. 2

EP 0 332 176 A3

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EUROPEAN SEARCH REPORT

Application Number

EP 89 10 4124

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
X	EP-A-0 251 342 (OXFORD MAGNET TECHNOLOGY LTD) * Page 3, line 1 - page 4, line 11; page 4, lines 33-36; page 6, lines 51-56; figures 1,2,6a,6b *	1,11,12,23	G 01 N 24/06 H 01 F 7/22
Y		3,6,13,14,18-21	
X	IEEE TRANSACTIONS ON MAGNETICS, vol. MAG-23, no. 2, March 1987, pages 603-606, New York, US; A. ISHIYAMA et al.: "Optimal design of superconducting magnets for whole-body NMR imaging" * Page 603, line 1 - page 604, end of paragraph: "Optimal design procedure"; figures 1a,b; figure 2a *	1,2	
Y	IDEM	3	
Y	EP-A-0 111 218 (BRUKER ANALYTISCHE MESSTECHNIK GmbH) * Page 2, line 9 - page 3, line 14; page 6, line 8 - page 7, line 9; figure 1 *	13,14,18	TECHNICAL FIELDS SEARCHED (Int. Cl.4) G 01 N G 01 R H 01 F
Y	REVIEW OF SCIENTIFIC INSTRUMENTS, vol. 56, no. 1, January 1985, pages 131-135, Woodbury, US; D.I. HOULT et al.: "Shimming a superconducting nuclear-magnetic-resonance imaging magnet with steel" * Page 131 *	6	

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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	15-10-1990	VOLMER J.W.

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EUROPEAN SEARCH REPORT

Application Number

EP 89 10 4124

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
P,Y	GB-A-2 197 487 (K.K. TOSHIBA) * Page 1, lines 89-104; page 2, lines 30-60; page 2, line 118 - page 3, line 8, figures 1,2,4a-c * ---	19-21	
E	GB-A-2 215 471 (FUJI ELECTRIC CO., LTD) * Page 2, line 3 - page 4, line 13; page 6, line 4 - page 7, line 11; figure 1 * -----	1,11-14,23	

TECHNICAL FIELDS SEARCHED (Int. Cl.4)

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
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